

Testing in Support of Fission Surface Power System Qualification

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Abstract. The strategy for qualifying a FSP system could have a significant programmatic impact. The US has not qualified a space fission power system since launch of the SNAP-10A in 1965. This paper explores cost-effective options for obtaining data that would be needed for flight qualification of a fission system.

Qualification data could be obtained from both nuclear and non-nuclear testing. The ability to perform highly realistic non-nuclear testing has advanced significantly throughout the past four decades. Instrumented thermal simulators were developed during the 1970s and 1980s to assist in the development, operation, and assessment of terrestrial fission systems. Instrumented thermal simulators optimized for assisting in the development, operation, and assessment of modern FSP systems have been under development (and utilized) since 1998. These thermal simulators enable heat from fission to be closely mimicked (axial power profile, radial power profile, temperature, heat flux, etc.) and extensive data to be taken from the core region. For transient testing, pin power during a transient is calculated based on the reactivity feedback that would occur given measured values of test article temperature and/or dimensional changes. The reactivity feedback coefficients needed for the test are either calculated or measured using cold/warm zero-power criticals. In this way non-nuclear testing can be used to provide very realistic information related to nuclear operation. Non-nuclear testing can be used at all levels, including component, subsystem, and integrated system testing.

FSP fuels and materials are typically chosen to ensure very high confidence in operation at design burnups, fluences, and temperatures. However, facilities exist (e.g. ATR, HFIR) for affordably performing in-pile fuel and materials irradiations, if such testing is desired. Ex-core materials and components (such as alternator materials, control drum drives, etc.) could be irradiated in university or DOE reactors to ensure adequate radiation resistance. Facilities also exist for performing warm and cold zero-power criticals.



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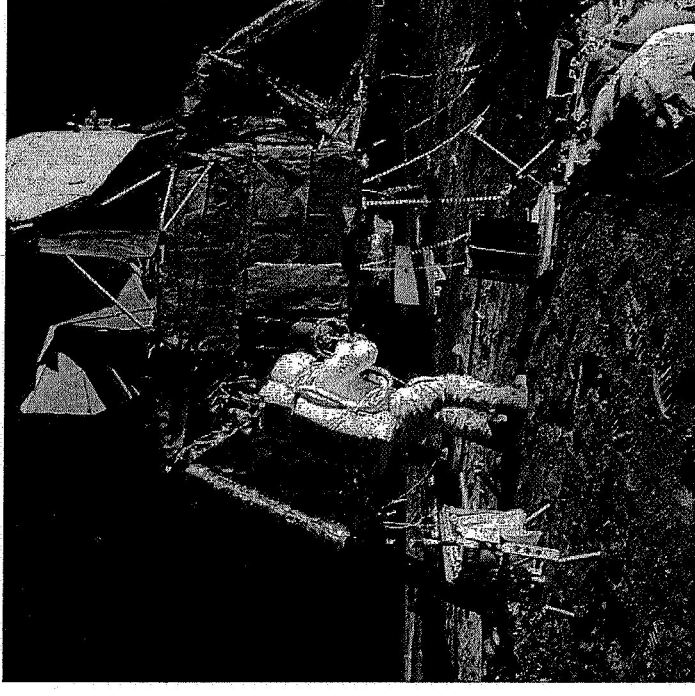
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Nuclear Surface Power Systems



- **Power anytime, anywhere on Moon or Mars**

- Operate in permanently shaded regions
- Operate through lunar night
- Operate through Mars global dust storms
- Operate at high Martian latitudes
- Extensible for operation anywhere in solar system or beyond
- Site Preparation, In-Situ Resource Utilization, Propellant Production, Fabrication, Life support, Communication, Mobility, Deep Drilling



- **First FSP use on a robotic mission?**

- Fission used early in architecture (sustain interest, facilitate future use)
- Land in permanently shaded region
- Deploy system, startup, operate, demonstrate shielding
- Provide heat and electricity for camp site / outpost
- Support science, permanently shaded ISRU demo
- Operational experience prior to first human mission

Previous Human Lunar/Mars Power Studies. Total Power Requirements 10 – 100 kWe. Option for Multiple Power Units.


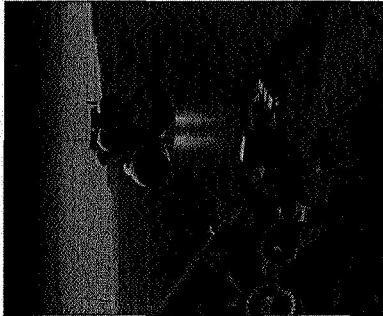
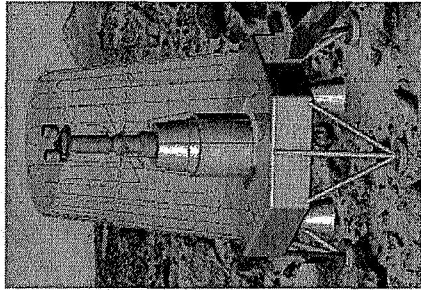
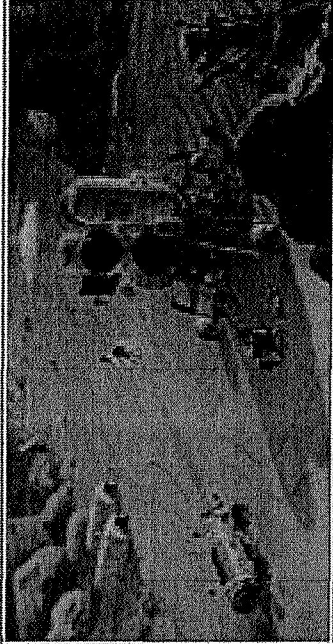


LUNAR						
Studies	Crew Size	Power Need	Power Type	Mass (mt)	Volume (m ³)	Comments
1989 Office of Exploration Technical Report	4 to 12	30 kWe-avg; 50 kWe-peak;	Nuclear reactor with power conv. Unit	4	27	
1989 90-Day Study	4	75 kWe- day, 37.5 kWe - night	Nuclear reactor with power conv. Unit			Lunar surface stay-time: 6 months
1990 Economical Space Exploration Systems Architectures	4	10 kWe	PV/RFC assemblies			Requirement for Lunar STV with habitat. Lunar surface base: 2-3 kWe per person for habitation.
1991 Synthesis Group Study	6	100 kWe	Nuclear reactor with power conv. Unit	12.5		
1992 First Lunar Outpost	4	12.5 kWe - day, 9.5 kWe night	PV/RFC assemblies	9.5		Integrated Lander/Habitat

MARS						
Studies	Crew Size	Power Need	Power Type	Mass (mt)	Volume (m ³)	Comments
1989 Office of Exploration Technical Report	4 to 7	30 kW _e -avg; 50 kW _e -peak;(Hab/W orkshop -100 kW _e)	Nuclear reactor with power conv. Unit	4	27	Long stay case studies chosen (lunar and Mars evolution)
1989 90-Day Study	4	25 kW _e cont.	PV/RFC assemblies			
1990 Economical Space Exploration Systems Architectures	4	25 kW _e	PV/RFC assemblies			Requirement for Mars STV with habitat Mars surface base: 2-3 kW _e per person for habitation.
1991 Synthesis Group Study	6	50 kW _e	Nuclear reactor with power conv. Unit	12.5		
1997 DRM 1.0	6	30 kW _e	PV/RFC assemblies	~77		Mass given is for Ha ² /Lab.
1999 Solar Electric Power System Analyses for Mars Surface Missions	4 to 6	40 kW _e	PV/RFC system	~10		Area of array: 5000 m ²
1999 Surface Nuclear Power for Human Mars Missions	6	25 kW _e	PV/RFC assemblies	14	390	Data similar to DRM 1.0

Planetary Surface Missions: Continuum of Energy Needs



 <p>Now: 290 We Deep Space</p> <p>General Purpose Heat Source - Radioisotope Thermoelectric Generator (GPHS-RTG) uses 18 Pu-238 fueled GPHS modules</p> <p>GPHS modules will be used by the 110 We Multi-Mission RTG (MMRTG, 8 modules) and the 110 We Stirling Radioisotope Generator (SRG, 2 modules)</p> <p>Thermoelectric</p>	 <p>1 kWe Radioisotope Surface (Rover or Stationary)</p> <p>Stirling energy conversion could allow 1 kWe to be generated using 18 GPHS modules (same # modules as 290 We GPHS-RTG)</p>	 <p>10-100 kWe Fission Surface</p> <p>Not affected by Pu-238 availability concerns</p> <p>Robust, power-rich environment anytime / anywhere</p>	 <p>100 – 1000 kWe Fission Surface</p> <p>Significant human presence on moon or Mars. Advanced human and robotic activities</p> <p>Extensive In-Situ Resource Utilization. Reduce propellant and consumable cost</p> <p>Closed life support systems</p>
<p>Thermoelectric</p>	<p>Stirling</p>	<p>Brayton</p>	<p>Advanced</p>
<p>MMRTG selected for Mars '09</p>	<p>Existing Heat Source Near-Term Option</p>	<p>Existing Technology Near-Term Option</p>	<p>Feasible Technology development needed</p>

Focus on “Workhorse” System Concept



- **Workhorse Definition**
 - Workhorse system is available/desirable once power requirements cannot be met by radioisotopes and/or stored energy. Desired module power level (based on previous studies) 10 – 40 kWe
- **Power level**
 - Fit on lander(s) to be developed for lunar exploration
 - Trade cost, technology risk, programmatic risk, and power level
- **Deployment**
 - 2018 or before
 - Anywhere on Moon, readily extensible to Mars
- **Mass**
 - Deploy using vehicles and equipment that will be developed for lunar exploration. Current assumed maximum allowable mass ~5000 kg.
- **Operation**
 - Initial system provides operational data to qualify for very long life (RTG, SIRTf analog)
 - Extensible to Mars operation
 - Shield to robotic requirements, regolith used to provide additional shielding
- **Minimize program risk. Minimize cost and difficulty of getting from current state to a flight qualified system. System must be safe, reliable, and affordable in a cost-constrained environment**

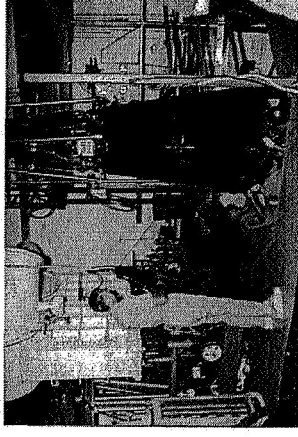
Workhorse System Must Be Affordable



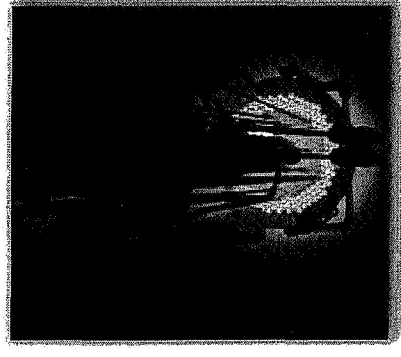
- A surface power system must be safe.
- A surface power system must also have adequate performance, reliability, and lifetime, and meet mass and stowed volume constraints.
- Once basic criteria are met, cost becomes the primary driver.
- JIMO / Prometheus-1: 20 year life; 208 kWe; Cat 1; Refractory metal fuel clad; Potential for refractory metal vessel; high temperature fuel/clad operation; overseas irradiation testing (JOYO), two ground tests, two flight units, power conversion - \$3.6B
- Fast Flux Test Facility (400 MWt, fast spectrum, sodium, research) – \$3.0B in FY06 \$\$
- 1371 MWe Commercial Light Water Reactor - \$2.2B
- 2-3 MWt TRIGA reactor (fully installed/operational, research capability, no power conversion) < \$50M
- Search for innovative approaches to reducing FSP development and utilization cost



~\$3B
(JIMO,
FFTF,
LWR)



"Modest"
Space
Reactor?



< \$50M
(TRIGA)

Qualification Testing for FSP Concept



The use of demonstrated technologies and well qualified fuels and materials would facilitate FSP system qualification.

The qualification testing strategy can also be optimized.

A robust, affordable test program will be needed to provide high confidence in mission success.

Information required for qualifying, launching, and operating an FSP system could be obtained from a combination of component / subsystem tests (both in-pile and non-nuclear), cold and hot nuclear critical tests, system modeling/simulations, “simple” non-nuclear system tests, and high fidelity non-nuclear system tests.

The fidelity of non-nuclear tests can be extremely high, if desired. The maximum achievable fidelity likely exceeds that required for development and qualification. The optimum desired level of fidelity should be determined early in the program.

Qualification Testing for FSP Concept



Focus on information required for qualification and operation.

Use of qualified fuels and materials will minimize need for additional fuels and materials testing. Perform component irradiations as needed.

Verify nuclear operating characteristics using cold and warm zero-power criticals

Design system to minimize the need to obtain data from a high power integrated system ground nuclear test. Design to be insensitive to parameters that could only be obtained from a high power integrated system ground nuclear test. Devise methods for validating codes.

High-Fidelity Non-Nuclear Testing Concept



Instrumented thermal simulators and facility designed to match axial and radial power profile (obtained from zero-power criticals or analysis) of FSP system. Data (temperature, pressure, flow, strain) gathered throughout the system, both from instrumentation embedded within the thermal simulators and at other locations.

All important parameters (temperatures, geometry, reactivity feedback coefficients) are measured. Required software uses measured data, not calculated. Not a "simulation" in the traditional sense of the word. Uncertainties can be incorporated into testing. Include design margins.

Transient testing is one application. Temperature and geometry changes within the core are measured following transient initiation. Reactivity effects are determined using reactivity feedback coefficients (obtained from zero-power criticals or analysis). Power to thermal simulators is adjusted as required.

Strengths Associated with High Fidelity Non-Nuclear Testing

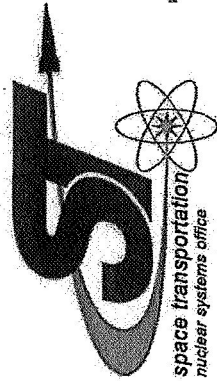


1. The system can be highly instrumented, allowing temperature, strain, and other measurements to be taken throughout the reactor.
2. Failure modes can be more extensively tested. Transients or events that would not be allowed in a full-power ground nuclear test can be tested.
3. The system can be fully inspected following testing, and the cause of failures can be more readily determined. Imminent failures can also be identified. It is difficult, costly, and time-consuming to inspect a system that has been tested with nuclear heat, and inspection is limited to that which can be done in a hot cell.
4. The full, integrated system can be tested using non-nuclear heat.
5. Cost/Schedule. "High Fidelity" non-nuclear testing is significantly less expensive than full-power ground nuclear testing. Turn-around time is also much shorter.

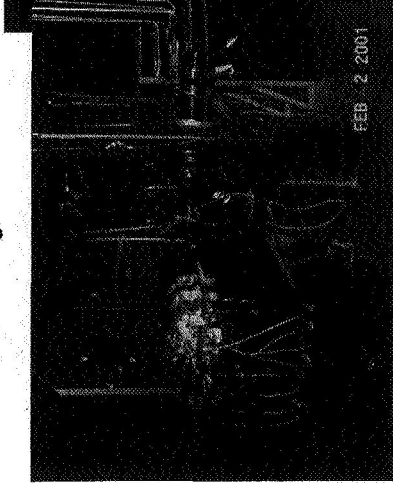
Weaknesses Associated with High Fidelity Non-Nuclear Testing



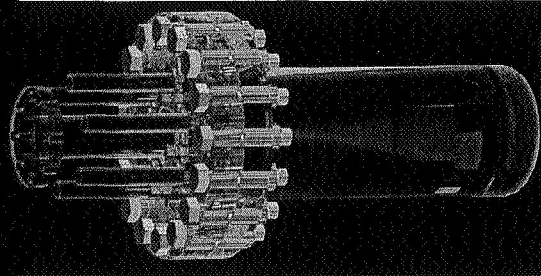
1. Penetrations needed to provide power to the thermal simulators may be non-prototypic. Calculations and experiments would need to be used to determine any thermal or structural effects from the leads or their sheaths. In the worst case, the flight unit would need to be designed to include dummy leads.
2. It can be difficult to mimic internal heating in some components (e.g. clad). The FSP systems under consideration operate at very low power density, which helps mitigate this issue.
3. Radiation damage effects are not present in high fidelity integrated non-nuclear system testing. Radiation damage effects would be assessed in separate component / subsystem irradiations. Effects will be mitigated by system design and the low system neutron fluence.
4. Axial power profile is assumed constant (axial power shape not affected by total power).



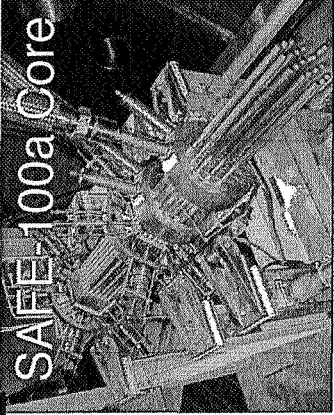
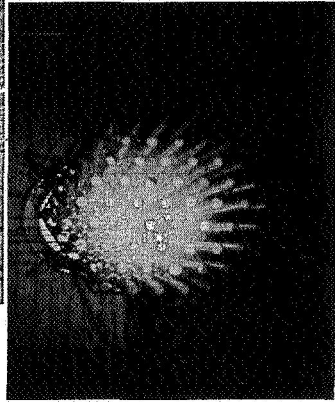
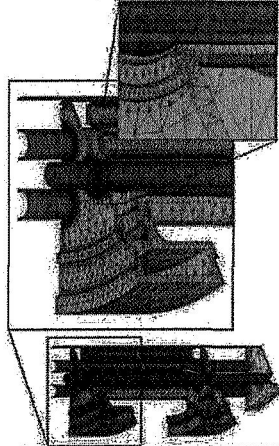
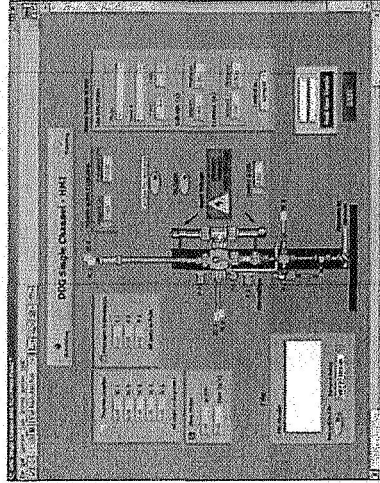
Realistic Non-Nuclear Testing for Thermal, Structural, Heat Transfer, System Integration, and Safety



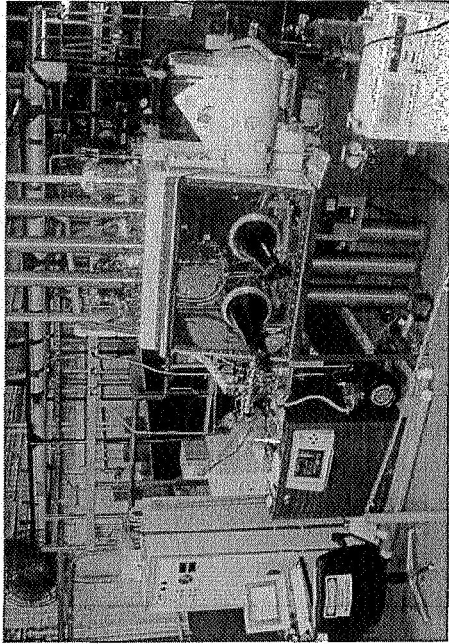
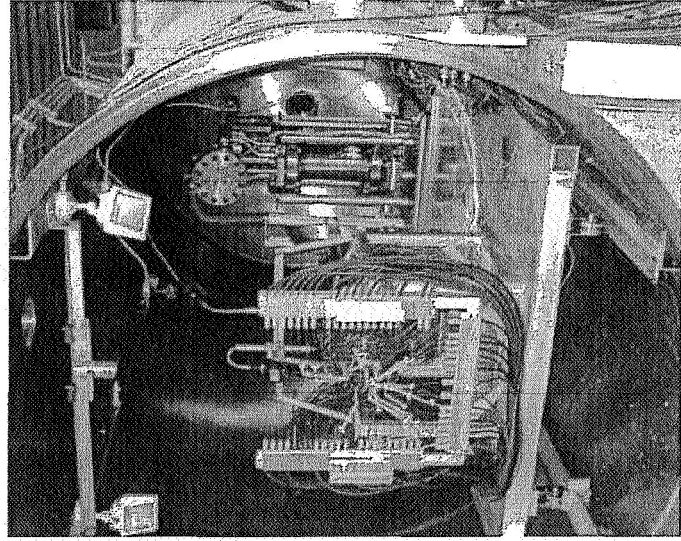
Single High Temperature Heater Evaluation



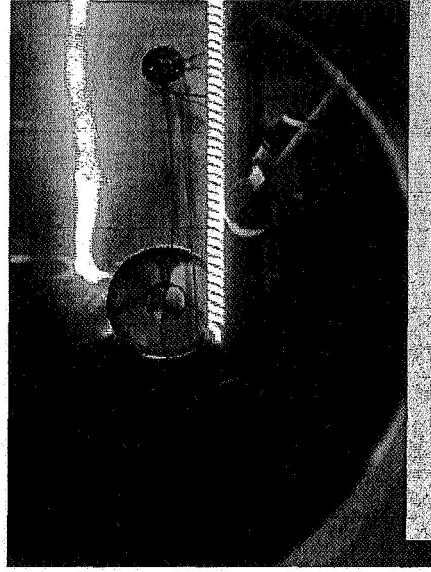
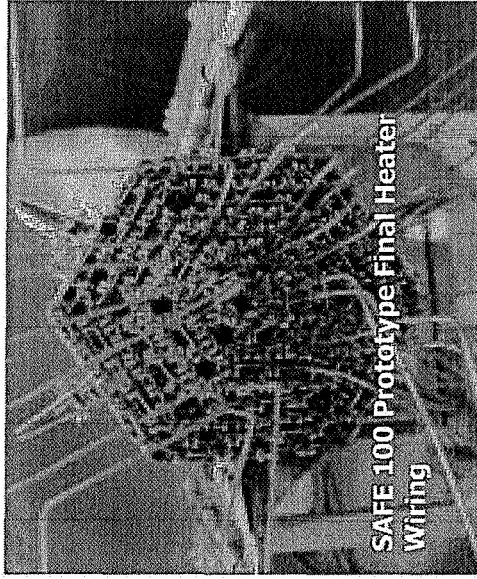
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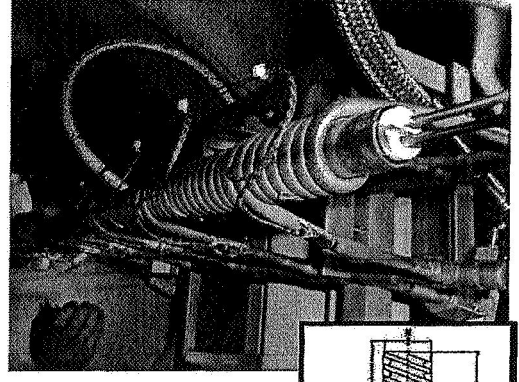
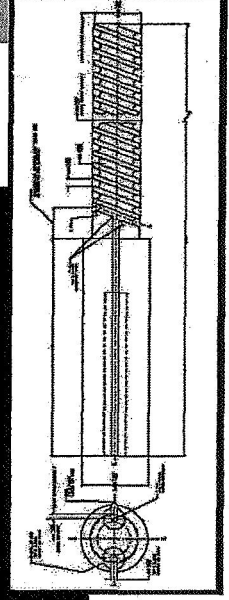
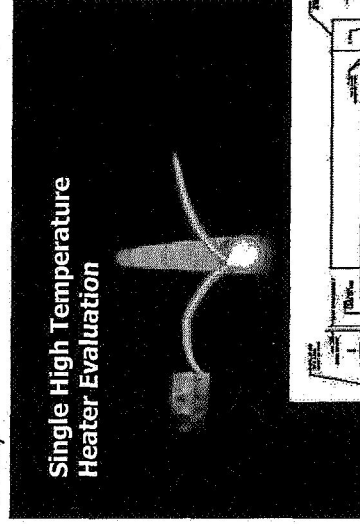
SAFE-100a Core

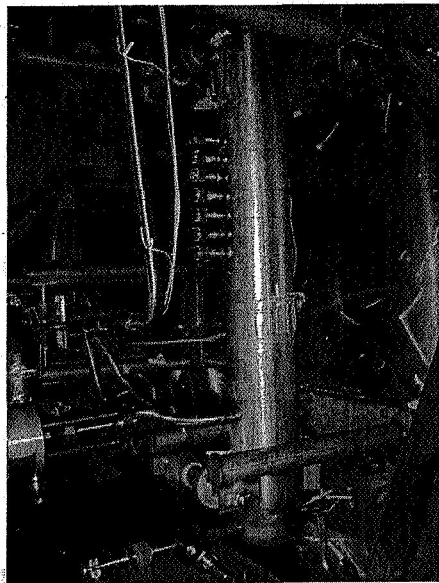


Thermal Simulators



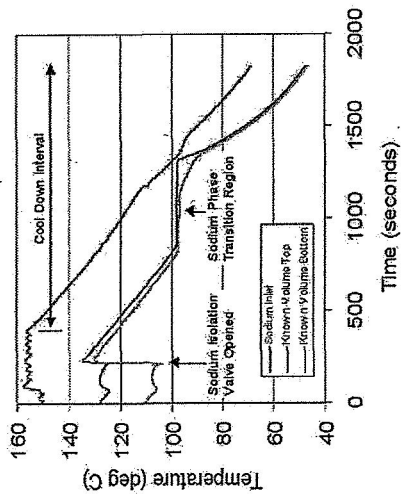
- Multiple concepts (shaped graphite, spiral wound, carbon fibers, brazed, etc..)
- Simulator design is a function of reactor concept. Demonstrated following parameters (individually, not necessarily an integrated assembly) :
 - High temps – demonstrated to 1500 deg C
 - High power densities – demonstrated 5 KW per pin (limitation is ability to remove heat from simulator) – Demonstration of carbon fiber braid
 - Long life cycles – demonstrated over 2000 hours and on-going
 - Axial power profiling – demonstrated distribution
 - Small pin diameters – demonstration of 0.65 cm (~SP 100 fuel pin size)
 - Materials contamination/compatibility and pin conductivity matching – demonstrated ability to “brazo within sheath” – sheath same material as core clad and provides ability to match conductivity
 - Integrated 183 pins in footprint of 25.4 cm (10 inch) by 30.5 cm (12 inch)



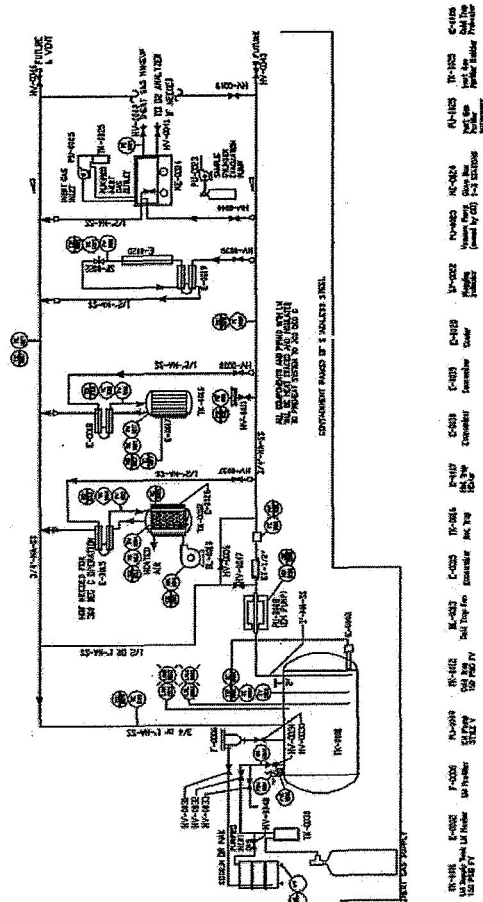


Purification and Manipulation of Alkali Metals

- Achieved <1 ppm Oxygen and Water Vapor
- Experience with Handling NaK, Na and Li
- High Purity Argon Distribution System
- Dri-Train and Ni-Train.
- High Vacuum System (<10⁻⁶ torr)
- TIG Welder System

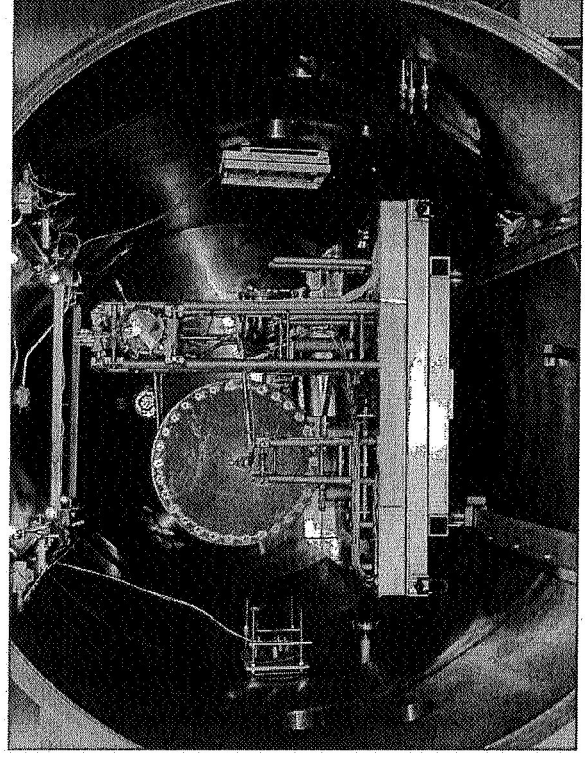
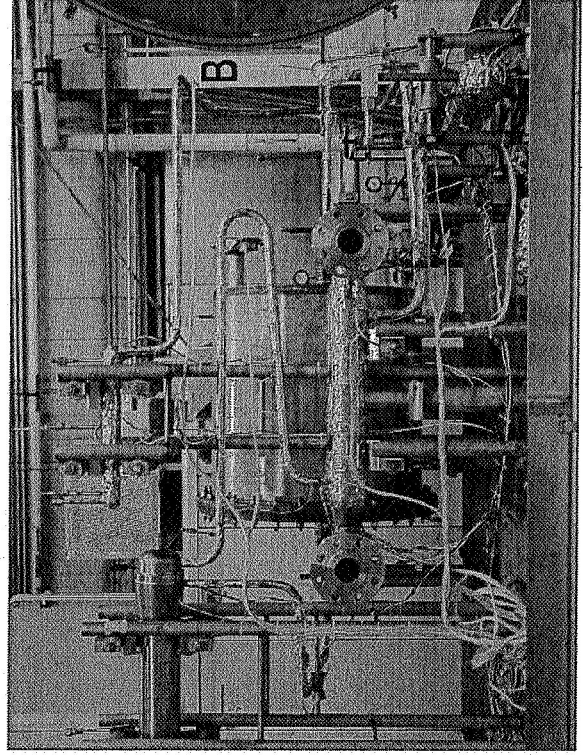
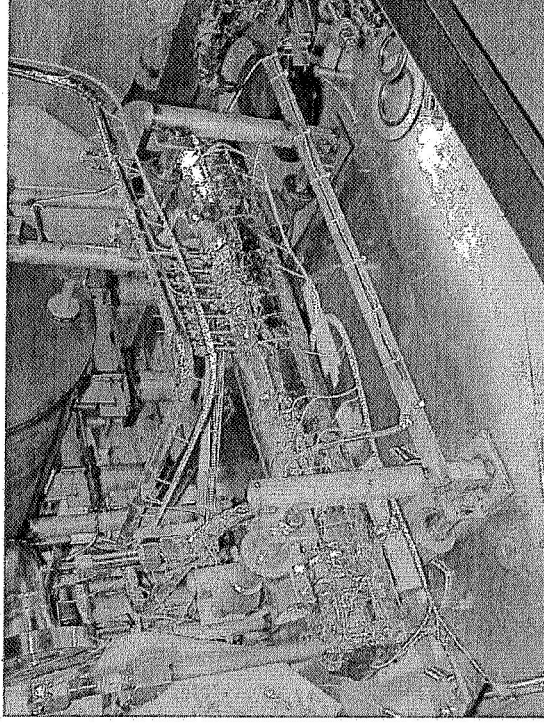
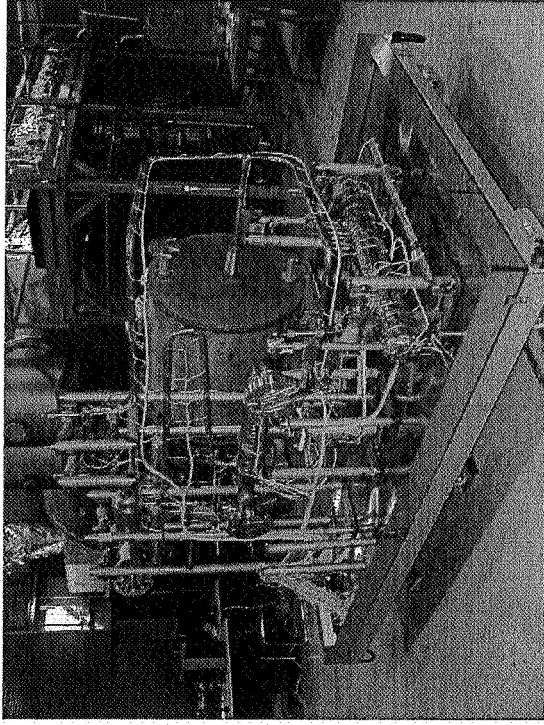


Sodium Purification System



Sodium Transfer

Fission Surface Power Primary Test Circuit (FSP-PTC)



Observations



Fission surface power systems have many attributes that could enhance or enable Vision for Space Exploration missions.

Previous and ongoing experience could facilitate development of affordable “workhorse” FSP systems.

Near-term work can reduce the technical and programmatic risk of FSP systems.

FSP qualification strategy can be optimized for effectiveness and affordability.